Robotic automation for space: planetary surface exploration, terrain-adaptive mobility, and multi-robot cooperative tasks

P. S. Schenker, T. L. Huntsberger, P. Pirjanian, E. Baumgartner, H.Aghazarian, A. Trebi-Ollennu, P. C. Leger, Y. Cheng, P. G. Backes, E. W. Tunstel, Jet Propulsion Laboratory; S. Dubowsky, K. Iagnemma, Massachusetts Institute of Technology; G. T. McKee, University of Reading (UK)

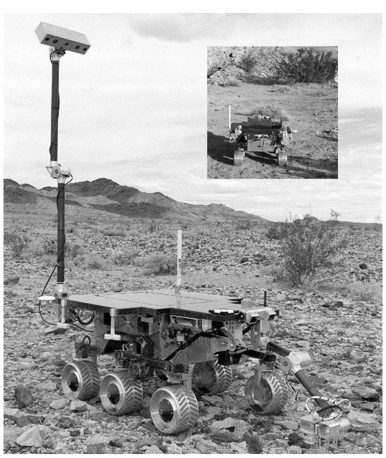
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive/MS 125-224
Pasadena, California 91109-8099
paul.s.schenker@jpl.nasa.gov

ABSTRACT

During the last decade, there has been significant progress toward a supervised autonomous robotic capability for remotely controlled scientific exploration of planetary surfaces. While planetary exploration potentially encompasses many elements ranging from orbital remote sensing to subsurface drilling, the surface robotics element is particularly important to advancing *in situ* science objectives. Surface activities include a direct characterization of geology, mineralogy, atmosphere and other descriptors of current and historical planetary processes—and ultimately—the return of pristine samples to Earth for detailed analysis. Toward these ends, we have conducted a broad program of research on robotic systems for scientific exploration of the Mars surface, with minimal remote intervention. The goal is to enable high productivity semi-autonomous science operations where available mission time is concentrated on robotic operations, rather than up-and-down-link delays. Results of our work include prototypes for landed manipulators, long-ranging science rovers, sampling/sample return mobility systems, and more recently, terrain-adaptive reconfigurable/modular robots and closely cooperating multiple rover systems. The last of these are intended to facilitate deployment of planetary robotic outposts for an eventual human-robot sustained scientific presence. We overview our progress in these related areas of planetary robotics R&D, spanning 1995-to-present.

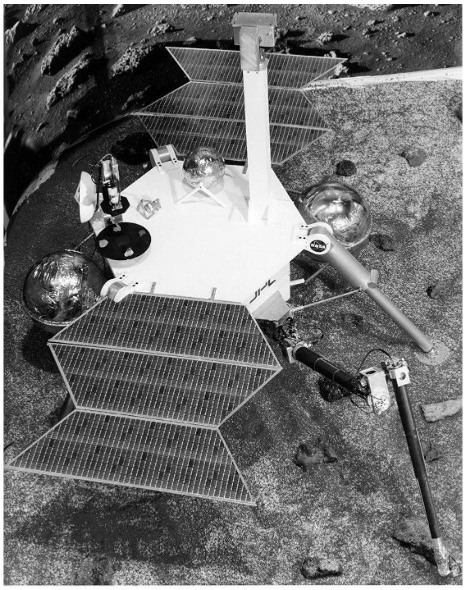
Keywords: mobile robots, mobile manipulators, robot architectures, robot control, intelligent control, machine vision, sensor fusion, modular robots, Mars exploration, NASA robotics

1. INTRODUCTION



There is growing international interest in a global exploration of the surface of Mars, more distant planets, and planetary moons. In particular, a better understanding of Martian surface geology, morphology, geo-chemistry, and atmospheric science will provide important insights to comparative planetary origins, potential for past/present Martian life, and capabilities of the Mars environment to sustain a long-term human-robotic colonized presence. There are many robotic options for Mars *in situ* surface science exploration. These include stationary landers, gravity-deployed penetraters, shallow and deep drilling platforms, subsurface "moles", low atmospheric density airplanes, touch-and-go balloons, and *semi-autonomous* surface mobility systems. The term "semi-autonomous" [1] connotes the remote planning, command-sequencing and visualization & interpretation of rover activity sequences and related data products by an earth-based science & engineering team—that is, operations wherein the command sequences and data returns are subject to extreme time delays and intermittent communications as imposed by at most daily uplink/downlink cycles of deep space networks.

Figure 1. JPL *FIDO Rover* in the field during a 1999 terrestrial mission simulation of Mars science activities (**http://fido.jpl.nasa.gov/**)



Past related robotics developments by our JPL group include a "MarsArm" lander-manipulator concept [2] that became basis for NASA's 1998 Mars Polar Lander, shown at left (Figure 2), as well as subsequent smaller mobile manipulator designs (e.g., the "MicroArm" series of our FIDO, SRR, and other rovers subsequently to be discussed). More recently, we have focused on mobile science and sample return, exploring various mobility design and operational concepts across a range of small-to-medium scale vehicles. The most mature of these is the <u>F</u>ield <u>I</u>ntegrated <u>D</u>esign & <u>O</u>perations (FIDO) rover, per **Figure 1**, previous page. The FIDO rover design and operational concept is representative of NASA's near-to-mid term program plans for Mars surface exploration, wherein emphasis is on longer ranging mobility and *in-situ* science. Such vehicles, operating "over-the-horizon" and free of lander constraints, will enable new kinds of remote planetary field geology. As one example, the upcoming NASA Mars'03 mission (<u>M</u>ars <u>E</u>xploration <u>R</u>overs) will greatly extend the physical and observational scope of an earlier 1997 NASA Mars Pathfinder/Sojourner flight experiment [3]—from 10's of meters about a nearby lander, upon which the rover depended for both area imaging and communications (carrying one rear-mounted instrument, the AXPS/Alpha X-ray Photon Spectrometer)—to 1000's of meters over variable terrain, using twin rovers capable of wide-area imaging and direct-to-earth communications (carrying a mast-mounted high resolution multi-spectral panoramic camera, near-IR spectrometer, thermal emission spectroscope, also, arm-mounted instruments such as a color micro-imager, Mössbauer spectrometer, and rock abrasion tool). In *Section 2*, we provide an overarching perspective of the FIDO rover, its field trial applications, and development environment design resources. *Section 2.1* outlines the FIDO concept, general architecture, operational approach and deployment into past field testing activities; *Section 2.2* treats the FIDO architecture in more detail, overviewing the software and functional organization of the vehicle. While the current NASA Mars exploration focus is mobile *in situ* science from larger platforms, there are later plans for a Mars Sample Return (MSR). In such scenarios, a rover not only carries out sample access and *in situ* analyses, but also performs sample extraction, containment, and ultimately a sample transfer for orbital ascent. One model for such MSR missions includes the sample collection rover's precision-guided return to an awaiting lander/Mars ascent vehicle complex and transfer of samples to same; another model considers use of a "sample cache" rover to actively retrieve collected samples from field sites (i.e., the samples have been previously collected by another rover or landed sampling system and are to be picked up by a precision rendezvous with same). *Section 3* surveys our related work in these areas, with emphasis on the problems of visual terminal guidance, state-fused rover navigation, and visually referenced mobile manipulation. The logical and desired evolution of Mars science rovers would also be to more all-terrain capabilities. There are numerous known and posited areas of the Mars surface that are not currently within safe reach of conventional rover designs, yet promise to be high in science content. In *Section 4* we highlight some recent work we have done to advance rover "terrain-ability" and safe navigation into adverse areas, e.g., steep and sandy slopes, and over highly variable surface features. A concept we are advancing at large is that of reconfigurable systems under behaviorally adaptive controls—autonomous capability to optimally adapt rover pose, c.g., and/or other quasi-static configuration parameters to observed/estimated terrain properties. Our most recent work extends this paradigm to cooperative interaction of modular platforms for collective estimation and distributed, decentralized control. As one case, we comment on our approach to steep cliff descent via multiple cooperating robots/rovers. As a more general approach to the problem of multi-robot cooperation, we have recently also been developing a class of system wherein multiple mobile manipulative robots operate under tightly coordinated kinematics and quasi-static force controls so as to carry out "work crew" like functions, the analogy being to construction tasks performed by human counterparts (and perhaps ultimately, in human-robot partnership). The goal of this research is to provide a technological foundation for planetary robots that can prepare outposts for later colonization, and or support more complex science (e.g., deploy a power station in advance of human arrival, or carry/deploy large aperture science instrument elements). *Section 5* gives a summary of our recent work in this area, presenting a novel robot control architecture that we have developed and demonstrated in support of extensible multi-robot cooperation in complex tasks.

Figure 2. JPL MarsArm lander-manipulator R&D prototype for stationary autonomous science exploration

2. FIELD INTEGRATED DESIGN & OPERATIONS (FIDO)

2.1 FIDO rover concept and testing

As noted above, FIDO is a technology integration and mission simulation testbed for semi-autonomous *in situ* science exploration. The usual operational paradigm for this class of rover is as follows: Based on down-linked panoramic imagery, as obtained from a rover-mounted camera/s, scientists designate nearby target(s) of interest to which the rover navigates via intermediate way-points. These are designed ground coordinate locations, as referenced to the rover world frame and/or features autonomously recognizable by on-board sensing (information which taken together constitute part of trajectory sequence planning). The rover visually detects and avoids local obstacles en route, while updating absolute trajectory coordinates. Rover localization over shorter distances is derivable from on-board odometry and inertial measurements; extended traverses are referenced to sun-sensor absolute heading. Either source can be supplemented by visual terrain tracking / matching. In any case, it is usual and safe practice to confirm a hypothesized rover position by ground analysis—contrasting latest rover down-link imagery with an expected position, re-initializing local position in a larger panorama, setting as needed new local coordinate frame references for science activities. In the case of FIDO, remote command and control is implemented via *WITS* (Web Interface for TeleScience), a JPL-developed toolset for cooperative, geographically distributed robotic science operations [4]. WITS, **Figure 3**, has diverse resources for science planning, 3D pre-and-post-visualization of sequences, uplink command-telemetry, science-engineering data product downlink/ display and more.

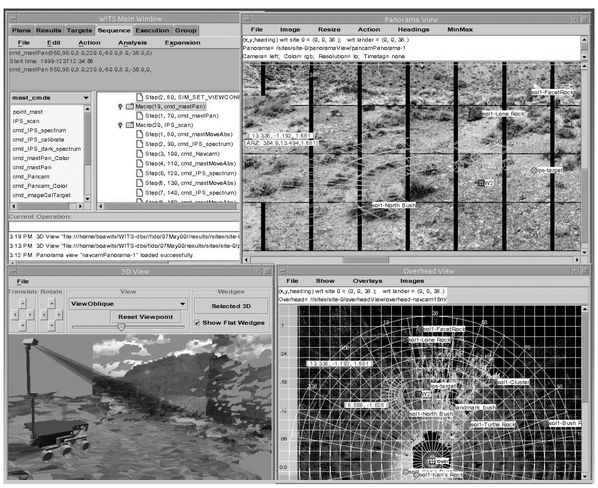


Figure 3. A Web Interface for Telescience (*WITS*) display as seen by a single operator at a PC/Unix-based workstation (Note that operators at different sites can simultaneously exercise different features and displays)

Table 1, next page, summarizes the key FIDO design features. These include: wide-area panoramic imaging (mast-mounted color stereo pair), 3D terrain mapping and hazard avoidance (B/W stereo navigation camera on mast; chassis-mounted front/rear stereo), visual self-localization (visual registration/tracking of natural and artifactual features), local path planning (with respect to derived stereo/navcam maps), inertial and celestial navigational references (e.g., accelerometers, gyro, CCD sun sensor [5]); and, finally, in reference to the above-cited rover localization issues, fused state estimation for long range navigational guidance (viz., statistical integration of odometry, visual, inertial, sun sensor and other data sources via Extended Kalman Filtering (EKF) and related techniques, per [6]).

We are characterizing FIDO rover—its underlying sensing, control, manipulation, sampling technologies and related remote science operational strategies—in an increasingly challenging set of science field trials under direction of NASA's MER'03 flight science team (PI Steven Squyres, Cornell University, co-I Raymond Arvidson, Washington University). A first trial at Silver Lake, California, in the Mojave desert, per Figure 1, demonstrated a "local sampling loop" about a putative lander site: panoramic imaging from the lander area, 3D navigational mapping to ground-designated targets of interest, open-loop traverses to selected targets, bore-sighted IPS imaging of targets in stand-off scanning and proximity pointing modes, kinematics-referenced 3D visualization and placement of mast/arm mounted instruments & tools, targeting and extraction of rock samples, and finally, return to the immediate area of the lander. A sequel field trial in spring 2000 at Black Rock Summit, Nevada, added significant new elements of Mars mission realism and complexity. In particular, operations were "blind" and fully remote. That is, the science team controlled FIDO rover by satellite communications from JPL and their prior knowledge of the site was limited to large area thematic and descent imagery typical of real Mars orbital observations.

The first action of the FIDO "Science Operations Working Group (SOWG)" stationed at JPL was to acquire a full panorama looking out ~ 50-100 meters and correlate this extensive visual data set with multi-source overhead thematic visible and infrared imagery (including LANDSAT7+, TIMS, calibrated AVIRIS, typically at 10-to-30 meters^2 per pixel resolution; the available data sets also included un-calibrated aerial photographs, oblique perspective views, et al.). Once so "situated", the

SOWG performed a prospective analysis of nearby targets of opportunity, ranking their science values against hypotheses about geological and mineralogical structure. Some targets were close enough to allow an immediate near-IR analysis via pointing of the mast-mounted IPS. This work done, the SOWG picked primary targets and commanded rover approaches. The terrain, as illustrated below (**Figure 4**), was quite challenging and rich. This motivated a very opportunistic, incremental exploration in which the investigators frequently stopped the rover, deploying its arm-mounted micro-imager to examine ground soils and rocks en route to a primary target. Figure 4 depicts one scenario element, with FIDO rover having already acquired and down-linked a panorama, and now beginning its local science in proximity of the 1:1 scale lander mock-up.

Mobility & Manipulation

- 6-wheel rocker-bogie, all wheels independently driven / steered
- max speed 9 cm/sec, 20 cm wheels, ground clearance 23 cm
- multiple mobility modes (turn-in place, “crab”, passive/active wheel drive); max obstacle clearance ~1.5 wheel diameters
- rover dimensions, 1.0m (L) x 0.8m (W) x 0.5m (H); 68 kg mass
- 4 d.o.f. articulated mast with integral science instrumentation
- 4 d.o.f. fully actuated and instrumented front science arm

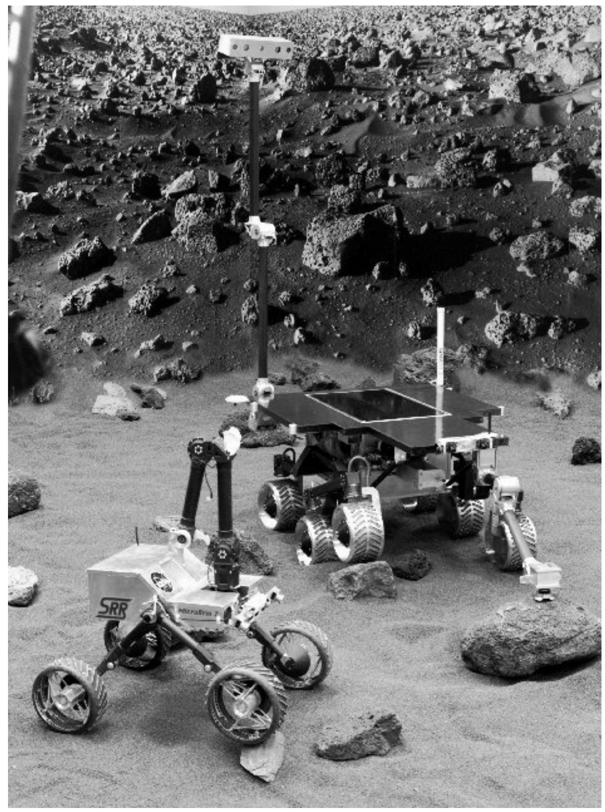
Navigation and Control

- PC104+, 266 MHz Intel Pentium, PCI/ISA bus, 64 MB RAM
- ANSI C software architecture under VxWorks 5.3 real-time OS
- front/rear hazard avoidance stereo camera pairs (115° H-FOV)
- mast-mounted navigation stereo camera pair (43° H-FOV)
- inertial measurement unit (IMU) and CCD-based sun sensor
- differential GPS for ground-truth reference of traverse

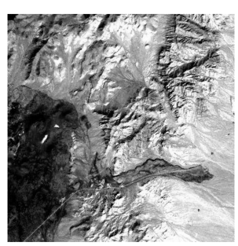
Science Instrumentation

- mast-mounted multi-spectral stereo camera pair (650, 740, 855 nm, 10° FOV, .34 mrad IFOV); full extent is 1.94 m
- mast-mounted near-infrared point spectrometer (1.3-2.5 microns, 9.3 mrad projective field of view)
- arm-mounted color micro-imager (RGB color, 512x496 pixel, 1.5x1.5cm2 FOV at approx. 3 mm standoff), and Mössbauer spectrometer; arm reach is ~50+ cm)
- rover-mounted Mini-Corer with belly stereo camera

Table 1. FIDO system features; for more detailed information on the various rover subsystems, see the JPL FIDO public web site **http://fido.jpl.nasa.gov**



[*FIDO Rover* and a *Sample Return Rover* (SRR) R&D prototype in JPL’s Planetary Robotics Laboratory]



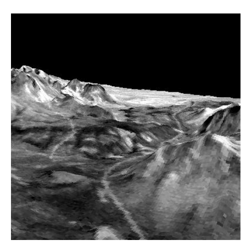


Figure 4. *FIDO Rover* at the Nevada blind field test, egress from lander complete, and beginning its science mission. Pictures at upper left and right: composite LANDSAT data and LANDSAT overlay of 3D TIMS reconstruction. See also **http://wufs.wustl.edu/fido**

In the aggregate, simulated Mars *in situ* mobile science of the year 2000 field trial was akin to terrestrial field geology [7]—a somewhat non-linear process of scientific discovery-and-discernment wherein multiple hypotheses were incrementally formed based on initial data and area history, then progressively updated, refuted, confirmed or dismissed (with at times the overall investigation being redirected as a new observation of yet higher perceived priority was made). The SOWG, science investigators, engineering, and operations staff learned a great deal from this multi-week experiment. Some of the insights gained were: 1) preferred science operational strategies and command-data sequencing protocols under fairly realistic time and bandwidth constraints; 2) limitations and impacts of open loop localization of rover and instrument arm placement in an interest area during target acquisition (processes involving coordination of rover motion with inverse kinematics positioning of arm-mounted instruments, also the rover-mounted mini-corer relative to 3D stereo maps taken from hazcam-bellycam-navcam); and finally, 3) the need for continuing development of 3D task visualization (supporting rover activity planning and instrument operations); resource models for sequence planning (time, power, data volume, etc.); and command-dictionary structure, downlink telemetry processing, automated report generation & data archiving, and overall task simulation, within WITS and related tools.

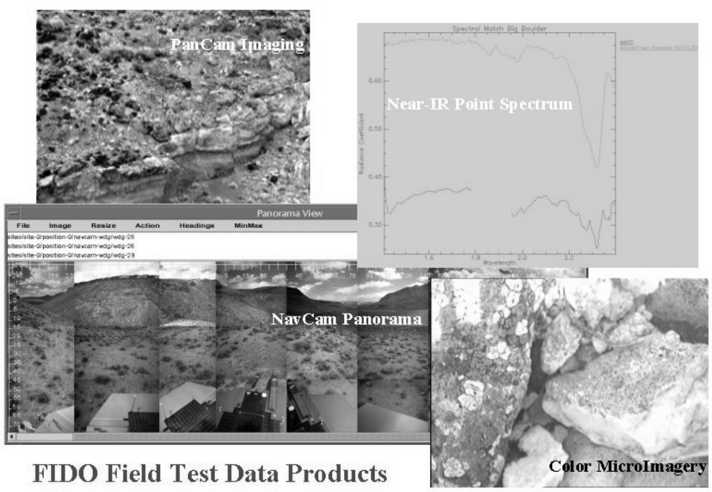


Figure 5. Representative data products from FIDO Rover field test at the Nevada. (Upper left), near-field Panoramic Camera sector; (lower left, Navigational Camera mosaic; (upper right), Infrared Point Spectrometer analysis of target; lower right, close-up of ground rock structure taken with micro-imager. See also **http://wufs.wustl.edu/fido**

In summary, robotic science experiments at this level of functional integration and mission scale yield significant insights to component technology capabilities and operational limitations; such investigations also provide serendipitous findings about operational strategies, e.g., interactive staging of the rover PanCam, IPS and micro-imager observations during driving; trends in global resource utilization, and, the most useful roles and relative merits of visualization and simulation tools.

2.2 FIDO architecture

This section highlights some key features of FIDO design approach—not just the current rover per se—rather, the overall concept of FIDO as a functional architecture and toolset for development of mobile, manipulative, autonomous platforms. At large, *Field Integrated Design & Operations is a set of common module design resources*, based in:

- mechanical hardware
- electronics and computing hardware
- sensors and actuators
- real-time on-board software
- mission operations software and tools

We have used these resources to rapid-prototype disparate robotic systems, per **Figure 6**, testing the resulting designs, embedded functions, operational concepts in wide-ranging mission scenarios. The "FIDO rover" itself is the most mature of these systems. In summary, *FIDO is a unified development environment and underlying system architecture for end-to-end mobile operations*. FIDO's efficiency as a cohesive design-and-implementation environment is strongly rooted in its software architectural approach. We sought an extensible and open design that would easily flow in new functional codes—also, in turn, enable its end users to extract successful products as very simple, compact, and generalized ANSI "C" routines.

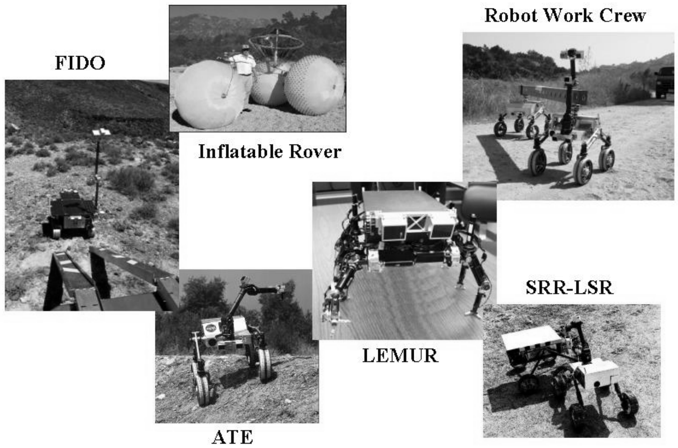
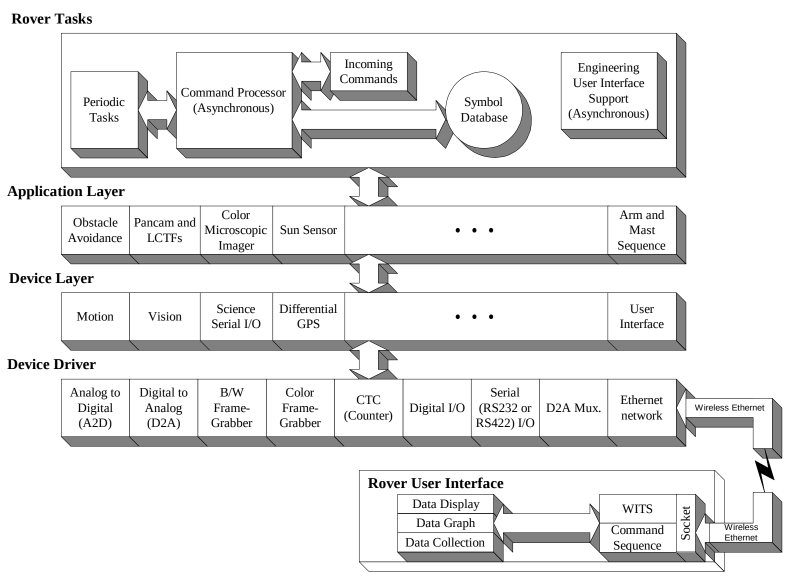


Figure 6. "FIDO family" to date, starting from left—FIDO rover; a long-ranging, high speed inflatable rover; multiple autonomous rovers that tightly coordinate kinematics and force constraints in "work crew"-like tasks; a small and highly autonomous Sample Return Rover for precision visual-guided field rendezvous and sample cache retrieval; a kinematically reconfigurable rover that can adaptively traverse extremely rugged terrain; and, last, a legged robot with modular tool change-out for space platform inspection maintenance and servicing



Operating System

- VxWorks 5.3 (Tornado)
- Turnkey bootable from solid state disk

Three Tier Architecture

- Device drivers (to hardware interfaces)
- Device layer (abstracted to generalized i/fs)
- Application layer (navigation/telemetry/etc.)

Software

- All code written in "clean" ANSI C
- Object oriented, modular, portable, small
- Supports multi-threaded tasking

Timing/Control Rates

- Hard periodic tasks run at 200 Hz, including
  - A/D conversion, encoder data collection
- Additional processes run off these tasks
  - Actuator motion control (50 Hz)
  - IMU data collection/processing (50 Hz)
  - Motion control synchronization (10 Hz)
  - Health monitoring (10 Hz)

Figure 7. Organization of FIDO software architecture and some of its key features

As indicated in **Figure 7**, the FIDO on-board real-time computing environment is self-supporting, with strong partitioning of specific hardware features/interfaces from sensor-motor functions via a generalized driver layer. This construct greatly enhances field-ability, and makes the integration of new sensing, control, and other code modules very transparent. Recompilation of code is straightforward, and indeed, we have readily performed in-field modifications using simple laptop development and debug tools. Overall we from the outset conceived FIDO architecture in the spirit of current design practice in modular, hard real-time aerospace systems: The real-time kernel is small; the executables are fast; the underlying code objects are small and general; the code structure is very general and open, carrying a minimum overhead in memory or OS support on re-integration; the development tools that support FIDO coding are widely available and understood, many of them being in the freeware domain. Thus, the FIDO environment as a whole is exceptionally attractive to migrate across new mobility platforms, and has become a significant R&D rapid prototyping resource in JPL's Planetary Robotics Lab that is cognizant for FIDO development. FIDO rover has to date logged 1000's hours of reliable field testing, often operating for extended periods, in diverse terrain, under quite adverse conditions (e.g, desert temperatures of 100+ degrees F).

3. ROVER RENDEZVOUS AND MARS SAMPLE RETURN

Figure 8 illustrates our recent development of a lander-based sample return operation. The mission concept that motivates this work is the idea of a science rover making repetitive "loops" into the field, periodically returning to a lander ascent vehicle, and depositing its latest acquired sample cache contents in a protective containment. The samples themselves are typically rock cores and nearby soil substrates; FIDO rover, as one example, carries a related "mini-corer" that has been demonstrated in the field under visually guided deployment for rock core sampling operations.

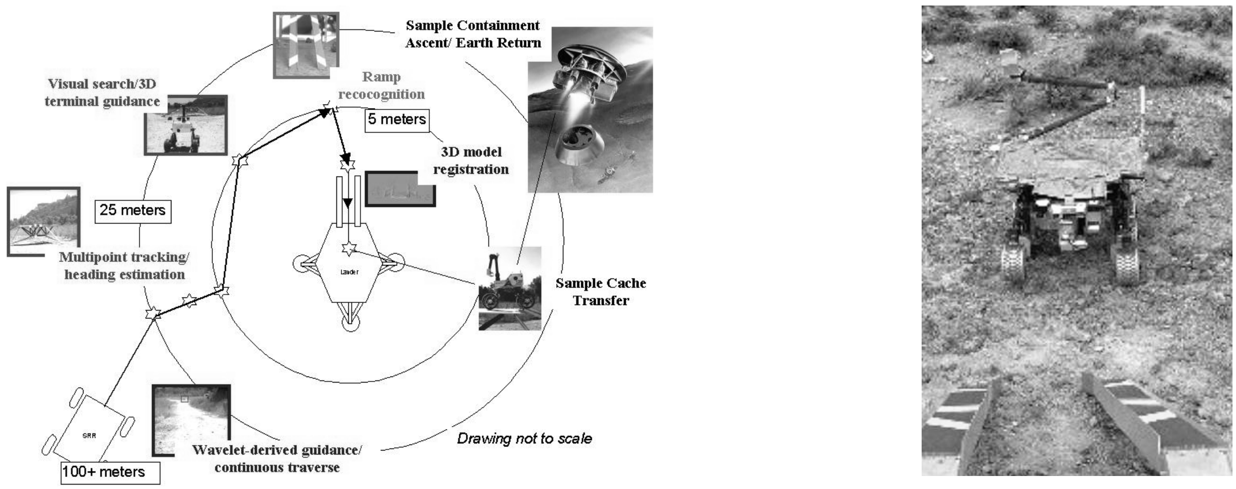


Figure 8. (Left) Operational scenario for rover rendezvous with Mars lander/ascent vehicle (the pictures within show our Sample Return Rover (SRR) research prototype; (Right) as implemented on FIDO, final approach in progress

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The objective, then, is to quickly rendezvous the returning science rover with a lander-based Mars ascent vehicle (MAV) complex. There are two underlying issues. First, the rover must determine location of the lander, then approach and physically engage it from considerable distances. Second, such operations must not be ground-intensive, requiring multiple uplink/downlink cycles per "loop"; rather, primary mission time must go to science. Thus, there is need to develop and demonstrate techniques for autonomous and accurate terminal rendezvous of the rover with artifactual structures. We note in passing that there are corollary mission scenarios, "on-board mini-MAV" and "in-field rendezvous". In the first case, having a small MAV as part of the rover platform itself finesses the rendezvous problem (This of course has its own implications as to rover size, sample transfer mechanization, etc). The second case has variants and is in the general spirit of using a small, fast sample return rover to interact with field repositories and science platforms—divide and conquer. We have explored the last mission scenario in some technical detail as regards the in-field rover rendezvous problem [8], and summarize some key results in **Figure 9**, next page. The direct-to-lander rendezvous approach by a single rover is the currently-assumed model for sample return in smaller rover missions; where it is feasible to fly a large entry payload, landing a significant fraction as mobile mass, then on-board MAV would seemingly might be preferred. We have used (per Figure 7) FIDO as a testbed for lander-rover rendezvous studies, in one case implementing such experimentation as part of the FY00 field trial. This development, as initiated in our Sample Return Rover task, and migrated to the FIDO vehicle, provides important new capabilities:

- autonomously detecting a Mars '03 replica lander structure from over 125 meters via wavelet-based techniques (similar to those used in Figure 8)
- tracking to a mid-range of 20-to-60 meters, then visually acquiring a more detailed multi-point geometric map of lander locations of interest
- approaching the lander closely (several meters), then developing a very accurate and robust fused feature map of lander structure, using same to move into closure of a meter or less, and finally
- registering (localizing) FIDO to within 1-3 cm and 1-2 degrees accuracy at the lander ramp entry point.

These operations are all done under sequentially staged autonomy, starting from fairly arbitrary approach directions.

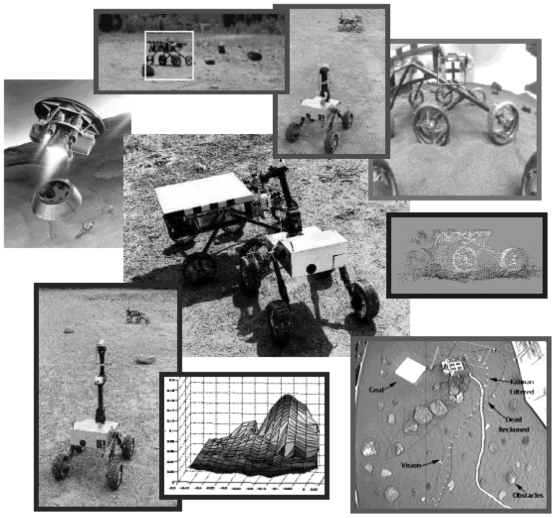


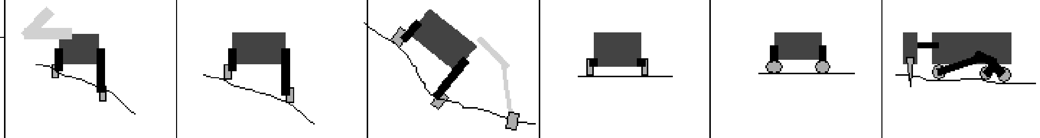
Figure 9. *In-field sample return rendezvous*: starting from lower left, the SRR (cache retrieval rover) in near-field approach to LSR (science rover) and mid-field obstacle avoidance; Mars ascent vehicle depiction; wavelet-based image localization of LSR from SRR goal camera; terminal goal-camera guidance and staging for normal vector approach; eigenvector-based recognition / localization of cache; 3D feature set of LSR used in final approach 3D registration/localization; rover experiment on fused visual tracking / odometry navigation; and bottom center, derived 3D map for hazard avoidance. In the middle, visually referenced sample cache pick-up. (NOTE: per reference [25], Lightweight Survivable Rover is an earlier-developed R&D concept for agile, low mass / power / computation, thermally-survivable mid-range science exploration about a lander.)

4. TERRAIN ADAPTIVE MOBILITY

The logical evolution of science rovers would be to more autonomous *all-terrain capabilities*. There are numerous known and posited areas of the Mars surface that are not currently within safe reach of conventional rover designs, yet promise to be very high in science content. E.g., there have been recent orbital observations suggesting water out-flows and attendant rich mineralogy near cliff edges. Thus, development of robotic mechanization and control architectures that enable roving into adverse, challenging terrain—areas that can change dramatically over short distances—is of considerable importance. We have recently undertaken related work, where the emphasis is having a rover autonomously adapt its real time control and geometry to estimated terrain conditions and observed system state—at behavior level [9]. **Figure 10** sketches the concept and scenarios that motivate it. The general approach is to have the rover image its forward-looking terrain, build from this a 3D map, analyze traversability characteristics relative to kinematic-and-quasistatic maneuverability/stability of progress, and enact compensating behavior that optimizes a rover performance index. The behavior is implemented on JPL's SRR in terms of reposing its stance and c.g. This is done in two ways: by independent articulation of the rover shoulder strut angles, and repositioning the rover top-mounted robot arm. Per Figure 10, the arm is treated as reconfigurable resource to be used in both kinematically unconstrained and closed-loop fashions, e.g., in the latter case, the arm acts as a drive actuator, pivot point, or other element in rover-ground interactions (as might be essential in some "de-trapping" operations). No consideration is given as yet to rover dynamics, as they are not a major contributory factor in the 5-to-10 cm/sec operational regime and low inertial mass/volume envelope we are treating. We do however, take into full account static friction-and-slip effects, treating these through kinematics and quasistatics analysis referenced to surface contact models.

In summary, we predict the future state of the rover based upon look-ahead stereo range imaging, on-board IMU, and any other derived state information that can be sensed, e.g., stall conditions, inferred slip from accelerometry; etc. This information is used to compute *a tipover-stability and slip-and-traction Locomotion Metric* [10], which determines possible and appropriate reconfigurations of rover geometry and center-of-mass. The algorithmic procedure is:

1. Determine the surface shape of terrain ahead of the rover (model by appropriate spatial representation).
2. Solve the configuration kinematics to predict rover configuration on the modeled terrain, i.e. roll, pitch, yaw, internal angles, and wheel contact points.
3. Given a friction coefficient that characterizes wheel-ground interactions, determine if the span of nominal frictional and normal forces at the predicted contact are sufficient to resist the *gravity wrench*, and any other disturbance forces, in both the nominal and re-configured kinematics/c.g. (wherein re-configuration consists of independent left-right shoulder angle changes as well as center-of-gravity shifts using the manipulator).
4. Determine the minimum coefficient of friction in Step 3. This term is interpreted to be a *Locomotion Metric* indicative of the quality of the given configuration.



Posture and Mobility Modes ⇨ / Detectable/ Predictable Conditions ⇩	Center-of-Gravity Rebalance	Shoulder Raise/Lower	Arm Ground Contact	"Belly Down"	"Crabbing"	Join/Split & Tethering
Traction Loss	Visual Odometry & Wheel Current				Roll/Pitch Sensing & Wheel Current	
Steep Slope	Roll/Pitch Sensing & Range Map	Roll/Pitch Sensing & Range Map		Range Map	Roll/Pitch Sensing & Wheel Current	
Wheel Trap			Wheel Current			
Support Loss			Acceleration & Tilt Sensing			Acceleration & Tilt Sensing
Crevasse						Range Map
Tip Over			Roll/Pitch Sensing			

Figure 10. Mobility reconfiguration in response to adverse terrain conditions.

Step 1 of the above procedure is implemented by stereo imaging—correlating Laplacian left/right images along epi-polar lines to establish image disparity, and consequently the range, via a camera model. Step 2 is computed by means of an iterative Newton Solver. Step 3 involves setting up polyhedral inequality approximations to the friction cone at each rover contact point, and expressing as inequalities the unidirectional constraints on the wheel normal forces and the wheel torque constraints. These linear relationships are then transformed to the vehicle frame using the vehicle *Locomotion Matrix* [10]. An equality constraint characterizes the manifold of contact forces able to resist the applied wrench without regard to constraints. A linear programming solution uses these inequality and equality constraints to determine if a feasible set of friction and normal forces exists to resist the applied wrench. A binary search algorithm then computes the metric by determining the smallest value of friction coefficient that suffices to resist the applied vehicle wrench.

We have implemented approximating approaches to this procedure through which we have achieved some very promising results to date. As an example, the rover has successfully made stable descents of 40-to-50 degree slopes and performed ascents and cross-traverses of 30 degrees or more, per Figure 11, at left.

Figure 11. SRR descending steep hill at Arroyo Seco near JPL. By comparison to operations under nominal fixed geometry and c.g. (i.e., with the arm in stowage position, and equal relatively low strut angles), rover tip-over instability is greatly improved.

Complementing work described above is a recent MIT-led collaborative experiment with JPL (S. Dubowsky et al.), performed on the SRR at JPL [11]. We next briefly summarize this study and some of its preliminary results. See also [12], for further details and background. By constrast to the previously described method and its “look-ahead” visual predictors, the MIT approach is based in an “instantaneous” analaysis of the rover state data for rover stability assessment and kinematic reconfigurability. The method does not require a detailed map of the terrain, rather only local knowledge of the wheel-terrain contact angles, which are estimated using simple on-board sensors [13]. Computational requirements are relatively light, recognizant of limited on-board resources of planetary rovers. Computer simulation and initial experimental results under field conditions show that such kinematic reconfigurability can signficantly improve rover stability in rough terrain.

The kinematic reconfigurability approach presented here relies on constructing a kinematic model of the vehicle in rough terrain, addressing tipover (Slip and frictional degrees of freedom are not addressed in this formulation). The key wheel-terrain contact angles are estimated using simple on-board sensors. Due to the slow speed of the rover (less than 6 cm/sec) only static forces are considered in calculating rover stability. System stability is expressed in terms of a set of stability angles. A stability angle is the angle formed between a line originating at the center of mass and normal to the tipover axis, and the gravitational (vertical) axis [14]. This angle goes to zero at marginal stability. A performance index, $\boldsymbol{\Phi}$, is defined for the SRR from stability angles γ_j, $i=\{1,\ldots,4\}$, and the reconfigurable shoulder degrees of freedom, ψ_1 and ψ_2, as **Equation 1**:

$$\Phi = \sum_{j=1}^{4} \frac{K_j}{\gamma_j} + \sum_{i=1}^{2} K_{i+4} \left(\psi_i - \psi_i' \right)^2 \tag{1}$$

where K_i and K_j are positive constants and the stability angles γ_j are functions of the shoulder and manipulator degrees of freedom (i.e. $\gamma_j = \gamma_j(\psi_1, \psi_2, \theta_1, \theta_2, \theta_3)$). Note that the first term of Φ tends to infinity as the stability at any tipover axis tends to zero. The second term penalizes deviation from a nominal configuration of the shoulder joints, thus maintaining adequate ground clearance, an important consideration in rough terrain. The goal of the stability-based kinematics reconfigurability optimization problem is to *minimize the performance index* Φ *subject to joint-limit and interference constraints.* For rapid computation, and given the simple nature of Φ, a basic optimization technique such as conjugate-gradient search is employed.

Simulation studies were conducted of the SRR traversing rough terrain. Results for a representative simulation trial are shown in **Figure 12** (left). In this simulation the manipulator and shoulder joints are reconfigured during the traverse. The stability margin of the fixed-configuration system reaches a minimum value of 1.1°, indicating that the system narrowly avoided tipover failure. The minimum stability margin of the reconfigurable system was 12.5°, a comfortable margin.

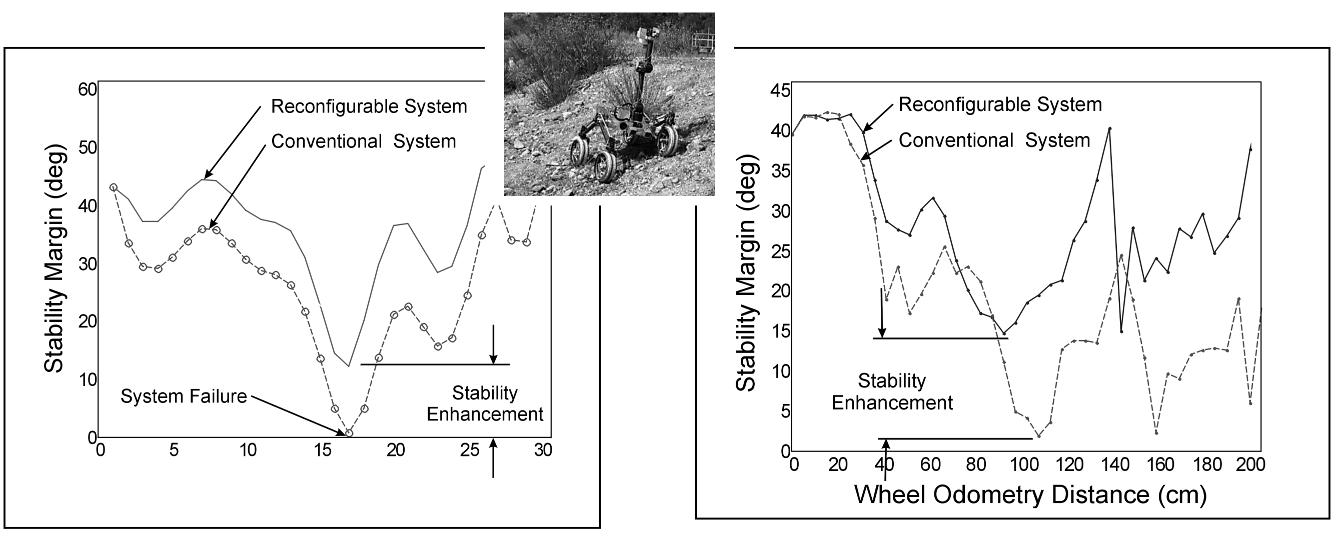
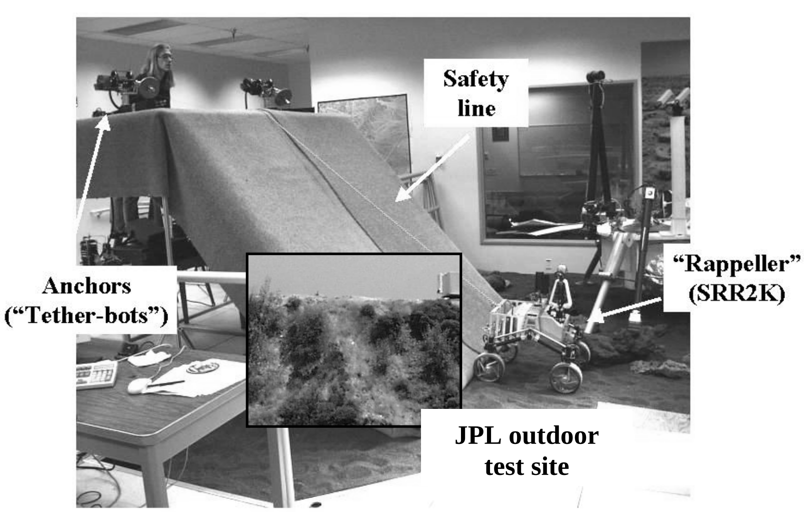


Figure 12. (*left*) Simulation: SRR stability margin for reconfigurable system (solid) and non-reconfigurable (dashed) system; (*right*) experimental data; (*upper inset*) SRR reconfiguring its geometry in response to unstable terrain

Physical experiments were also performed using SRR in the JPL Planetary Robotics Laboratory and the adjacent Arroyo Seco in Altadena, California, by a joint MIT/JPL team of researchers. SRR was commanded to traverse a challenging rough-terrain path that threatened vehicle stability. For each trial, the path was traversed first with the shoulder joints fixed, and then with the kinematic reconfigurability algorithm activated. Results of a representative trial are shown in **Figure 12** (right). The stability margin of the fixed-configuration system reaches dangerous minimum values of 2.1° and 2.5°. The minimum stability margin of the reconfigurable system was 15.0°. Clearly, kinematics reconfigurability can result in greatly improved vehicle stability in rough terrain, as predicted at left.

In closing this section, it is useful to note that the overall paradigm for all terrain exploration (JPL based work) is behaviorally motivated. The operational concept rests in a JPL architecture, further described in the next section, wherein lower levels of control are reactive to multiple state observations (including possibilities of coordinated-collective sensor and control actions across multiple platforms/agents), and higher level guidance may be derived from a deliberative planning level (itself also potentially decentralized in both its computation and communications). Thus a hierarchy of sensor, model, and ultimately task-based adaptation is made possible, and desired. There are linkages to our earlier R&D including that on lander-based autonomous manipulation per Figure 2. One novel aspect of that earlier research was our related development of a supporting Goal Oriented Behavior Synthesis architecture [2, '97] facilitating the arm's autonomous detection and control of anomalous events, e.g., encountering and circumventing a hard-soil impediment to digging. In a yet broader context, we have also investigated task-driven behavioral controls wherein the context is cooperative human-robot interaction under remote control [1]; the results included demonstration of long-distance "tele-programmed" operations where a distant manipulator made local autonomous event-driven corrections/compensations of its actions in response to the remote human operator's higher level kinematics planning/guidance. Returning to the immediate concern of this section, **Figure 13** below gives one example of the direction we are now headed as regards modular-reconfigurable surface mobility. In this scenario, multiple robots (two FIDO-computing-based tetherbot emulators and one actual SRR-derived robot) cooperate to enable an actively controlled cliff descent, including terrain-mapped obstacle avoidance on slopes up to 75 degrees. There is strong motivation to develop such future capabilities for Mars as recent orbital observations suggest very rich and informative sedimentary deposits exist as a result of historic cliff edge water outflows. Robotic access to these basal and higher cliff regions could be very important to the central "follow the water theme" of Mars surface science exploration. As this paper is being written, we have begun natural terrain experiments with the "cliff-bot" system shown below (The picture inset shows one candidate region). Several fundamental technical issues are being addressed and are further discussed in a related paper of this symposium [15]:

- Way-point navigation: synchronization of velocity for rappeller robot motion and tether-bot anchors' pay-out speed.
- Stability: a) collective estimation for identification of unstable conditions; b) collaborative avoidance/recovery from same
- Conflict resolution: consolidation of the two potentially conflicting criteria (stability vs. way-point) utilizing multi-objective optimization , wherein unstable situations are used as constraints (cf. CAMPOUT, next section of paper)



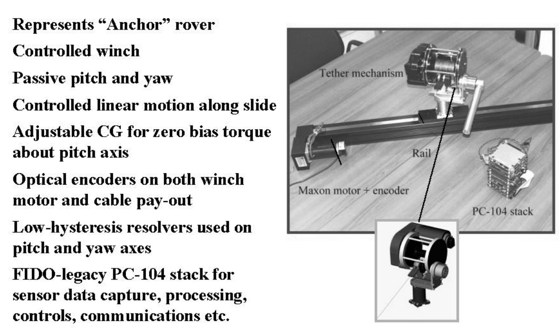


Figure 13. System concept and preliminary lab integration for multi-robot cooperative cliff descent by a SRR/terrain adaptive robot (note: for summary details of SRR/SRR2K implementation, see **Table 2**)

5. MULTI-ROBOT COOPERATION AND NETWORKED ROBOTICS

There are a number of surface mission scenarios that could benefit from, and directly motivate distribution of activity across multiple rover platforms [16]. This need goes well beyond "passive" cooperation, e.g., above examples where one rover performs precision rendezvous with another rover/robot for purposes of manipulative sample cache pick-up, transfer, etc. As noted above, a predominant driver is future Mars outposts, in which robots will act as precursors to human exploration, and once human presence is achieved, remain essential infrastructure for sustained habitation. There are of course related roles for systems of cooperating surface robots. Examples include groups of closely coordinating robots to handle/integrate large aperture optical instruments, and the deployment of "networked" science systems ranging from local incoherent imaging (e.g., long-baseline stereo) to more geographically dispersed structures with some degree of accurate on-line metrology.

We next outline our recent development of a new robotics architecture, "CAMPOUT"—and its experimental demonstration in mobile multi-robot cooperation focused on shared physical tasks [17]. The analogy is the human work crew in construction where two or more crew workers are called upon to carry an extended object over obstructed terrain, performing object acquisition, transport, and deployment (akin to the "piano mover's problem", and scenario requiring a high degree of shared state knowledge!). Challenges to this *Robot Work Crew*, as we call it, are major in that achieving a generalized performance requires tight, instantaneous coordination of kinematics and force constraints between the two robots over variable surfaces, subject to pre-emptive behaviors that must manage obstacles and anomalies, all within a non-holonomic space. Most related research has treated the problems of multi-rover cooperation as sequenced interactions, versus closed loop, real-time kinematics coordination under force constraints. Work that does address such "tight coordination" is in most cases is restricted to idealized environments—lab floors. Real terrain operations are significantly different: we have found in simulation and practice that as little as two degrees differential inclination of the rovers/payload can introduce significant control complications.

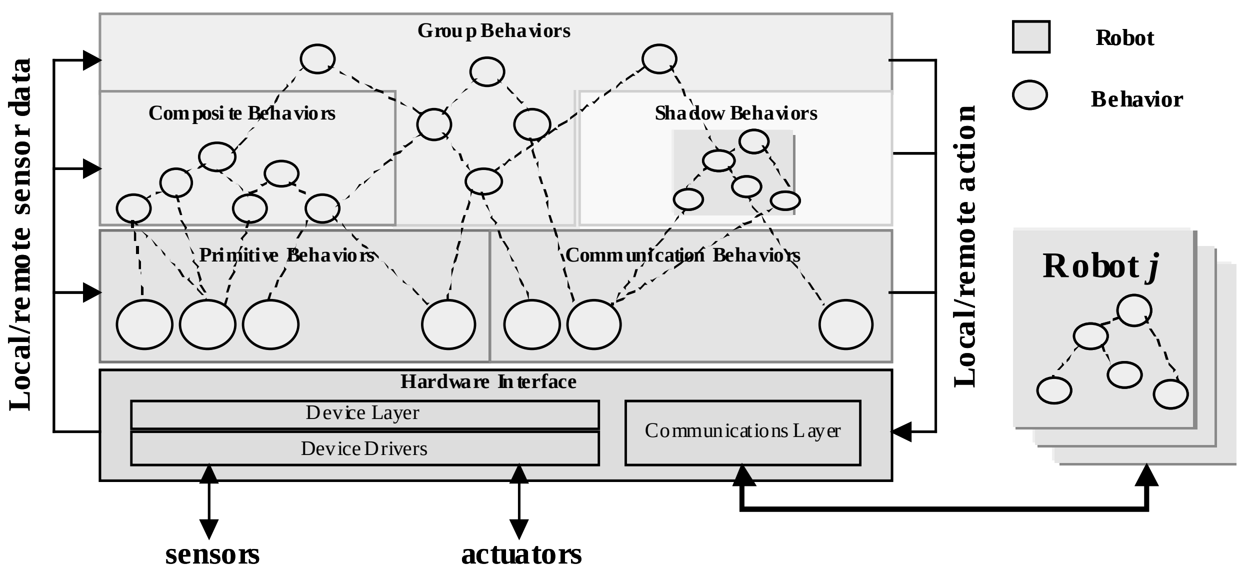


Figure 14. Functional organization of the JPL Control Architecture for Multi-robot Planetary Outposts (***CAMPOUT***)

We present our more detailed approach to multi-robot cooperation in [17, 18], including the research priors, and give details of our underlying control architecture in [19]. Here, we briefly sketch the concept, its major architectural features, and one recent significant field experiment conducted in natural terrain.

2.1 Tight coordination of mobile robots

A long duration mission such as a robotic outpost on a planetary surface has wide ranging needs—from low-level, highly reactive components supporting immediate local navigation and manipulator control, to higher-level planning of large-area/duration tasks. *CAMPOUT*, **Figure 14**, is an architecture we have developed that spans a range of tactical-strategic requirements via low-level control drivers directly tied to actuators, commanded in turn by a behavior-based control hierarchy

(Figure 15), overseen by a higher deliberative task planning layer. CAMPOUT is highly distributed. Advantages of distributed control and coordination include the efficient use of system resources, parallel execution of multiple tasks, reliability and fault-tolerance to failure of individual components (including failure of single robots). Behaviors within a single robot operate in a distributed manner, thus allowing concurrent and/or parallel execution of several tasks. However, each robot can operate on its own, independent of other agents, based on its inherent faculties of perception and action. Cooperation between the multiple robots occurs through active collaboration—there is no centralized planning or decision-making to dictate explicit commands. Note that *reactive behaviors* facilitate tight perception-action feed-back loops that can promptly address unexpected situations; behaviors are in turn guided by *deliberative plans* for efficient use of global system resources. In effect, in CAMPOUT, the role of plans is to guide, not dictate the control of reactive components. CAMPOUT provides a number of so-called coordination mechanisms that are tailored for not only cooperative, but also tightly coordinated tasks. Behaviors are organized in a hierarchy wherein higher level abstract behaviors are built upon less abstract behaviors and so on. Each behavior has an objective that it pursues by coordinating subordinate behaviors. Thus, behaviors can have two roles in an agent: as *actions* and as *action selection mechanisms*. With respect to its subordinates, a behavior is an action selection mechanism; with respect to its superior, a behavior is viewed as an action to be implemented. This approach is attractive for its low computational and communications overhead.

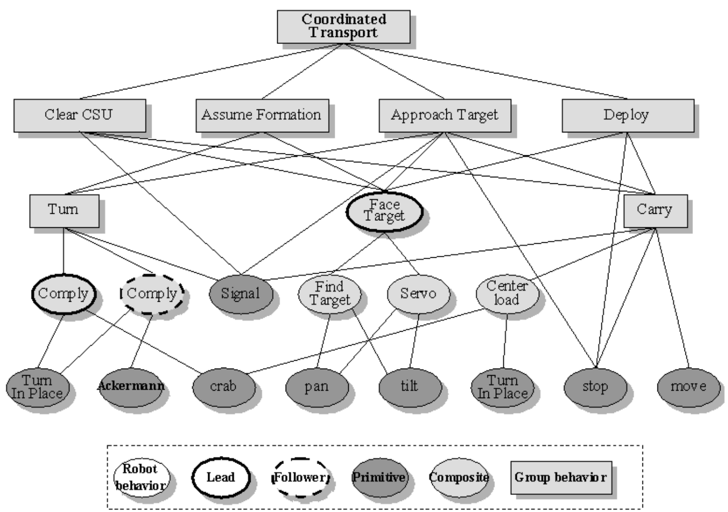


Figure 15. A CAMPOUT behavior hierarchy describing coordinated transport (as illustrated in Figure 16 below). Bubbles represent single robot behaviors and boxes represent multi-robot "group" coordinated behaviors. High-level actions, themselves behaviors, are composed from yet lower-level behaviors.

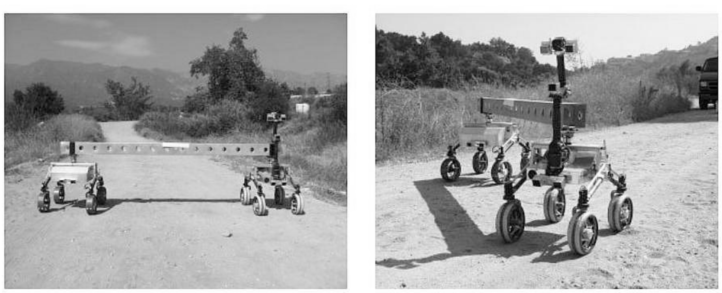
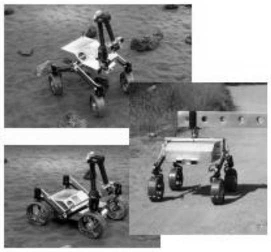


Figure 16. Coordinated transport of extended payload (2.5 meters) by SRR and SRR2K, performed in the Arroyo Seco near JPL. (Left) row transport formation; (Right): column (leader-follower) transport formation.

Objects many times the length of a single mobile platform are difficult to manipulate and transport. The *Robot Work Crew (RWC)* concept uses multiple rovers for cooperative operations on such extended payloads. These tightly coordinated multi-robot operations are implemented on SRR platforms, as illustrated in **Figure 16** and summarized in **Table 2**. The baseline SRR design is reported in [8], wherein it incorporated skid steering and functions for stereo-based obstacle detection, continuous motion visual traverse (10-15 cm/sec), visually-servoed manipulation, in-field visual object detection, tracking, rendezvous, et al. More recently, we have augmented SRR design with 4-wheel steering, improved computational resources, the above described CAMPOUT behavioral control architecture, and gimbaled grippers that enable compliant payload handling (Fully-actuated handling/transport of extended structures may not be realistic for planetary surface operations due to mass/power/computational constraints). We initially investigated an instrumented passive gripper design per **Figure 17**, and as subsequently reported herein, have recently augmented both rovers with more dexterous manipulation capability.

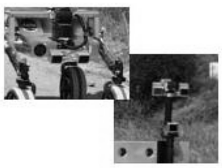


Mobility and Configuration Control:

- 4 wheel independent steering with full instrumentation and capability of up to 3 N-m and 3 rad/sec
- 20 cm dia. wheels with odometry capable of 19 N-m and 21 cm/sec
- Passive, instrumented, rocker-type suspension with active spur-gear differential articulated shoulder joint
- Parallel linkage on suspension enables simultaneous operation of articulated shoulder/passive rocker/steering

Multiple Rover Operations:

- Fully instrumented 4 DOF (pitch, roll, yaw, lateral translation) gimbal
- Compliant gripper for "soft-grip" of payload
- Interchangeable payload support beams to increase the load carrying capacity



Computing, Electronics:

- Pentium 266MHz/32MB, VxWorks 5.4, Solid State Disk (boot-able)
- 2x4-axis mot. ctrl., 2x640x480 color framegrabber, 12bitx16ch D/A
- Ethernet (~1.5 Mb/s) wireless modem; 24v battery pack, 1-1.5 hr.
- stereo b/w pair 120° FOV; arm-mounted stereo color pair 45° FOV; arm-mounted 20° FOV goal camera

Table 2. Summary of JPL *Sample Return Rover* (*SRR*) features ('00)

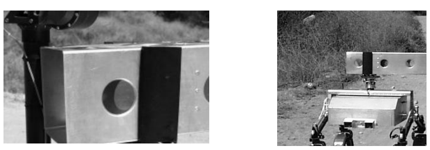


Figure 17. Instrumented gimbal (close-up at left)

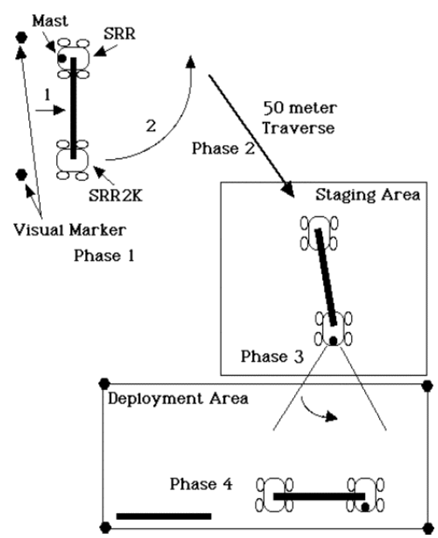
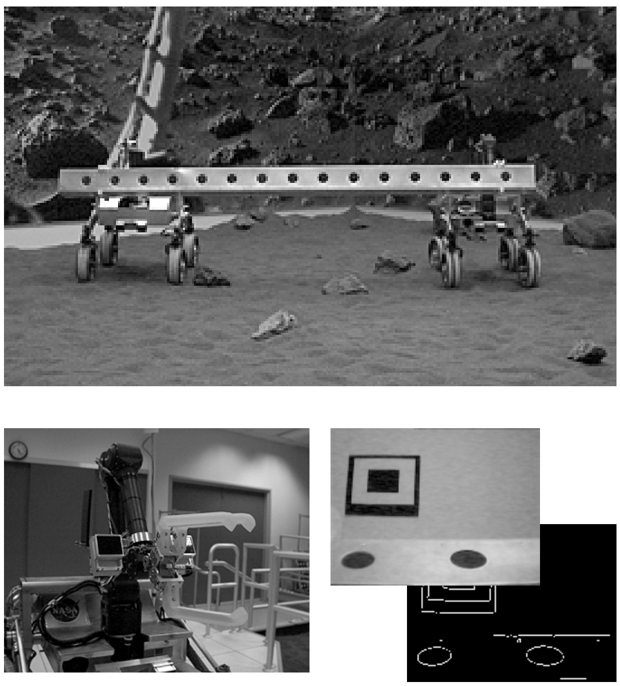


Figure 18. 1) Initiate transport configuration; 2) Move to staging area; 3) Initiate site survey; and, 4) Dock.

The gimbal is attached to a cross brace that spans the shoulders of the SRR and has three degree of freedom force sensors and potentiometers for monitoring the container relative to the rover body. Our goal in this experimental study was the transport of an extended container (12.5cm X 12.5cm X 250.0 cm) by two rovers (SRR and SRR2K, the latter being a minimalist version of the first) from a pickup point to a deployment zone that is up to 50 meters away, over un-occluded natural terrain. This was accomplished with the four-phase sequence of **Figure 18**. We provide a detailed description of the experimental implementation using CAMPOUT in [19], including the specific sensory-control behaviors and their higher level compositions (see also [20]). As a general operations strategy, we minimize explicit communication between the rovers (as would reflect possible operational constraints during an actual mission). This is facilitated by using the shared container as an implicit means of communication—e.g., relative positions of the rovers are known through the yaw gimbal angle on each rover. Also, we are exploiting natural design constraints of the task where possible to assess useful trades of mechanized cooperation versus explicit control (as one example, the use of passive compliance in both grippers along the beam axis).

Our continuing development of the robot work crews focuses on more challenging elements of the *transport* problem—e.g., cooperative obstacle avoidance—as well as the corollary payload *acquisition* task, wherein the two robots must initially must establish a precision rendezvous with their payload and then carry out the necessary coordinated actions of mobility and cooperative grasp-positioning/verification at the two payload end-points. **Figure 19** shows our early lab implementation of this acquisition experiment, with testing of a full-scale scenario now underway in the JPL Arroyo Seco. Further details of the work are presented in another paper of this symposium [15].



- CAMPOUT capabilities added for manipulation with provision of new behaviors for grasping and lifting of extended objects
- Grippers designed/added to SRR's MicroArm2 and SRR2K's MicroArm1, including contact switches
- Integration and testing of simple behaviors underlying the _Coordinated Grasping_ and _Coordinated Hoisting_ "group behaviors" within CAMPOUT
- Integration and testing the _Get Clear Path_ simple behavior used by the team planner rover for obstacle avoidance by two rovers carrying an extended object
- Implementation of feature targeting algorithm that determine rover position from ranges of 120 cm to 55cm (currently observed lateral error is < 1cm; distance error is < 0.8cm).

Figure 19. Experimental development of payload acquistion concept for a simulated Mars robotic outpost power station deployment (The payload simulator represents a photovoltaic tent array in its containment [17, and references therein]).

In closing, we note that the work above, as well as decentralized sensing and control of modular robotic systems for adverse terrain exploration is part a larger conceptual framework—*networked robotics*. The essence of networked robotics is the notion of distributed resources providing one or more interactive services [21, 22 and refs. therein]. Sensors (vision, range, position, etc.), effectors (manipulators, mechatronic modules, grippers, mobile platforms) and computational units (fused state estimation, mapping, planning and navigation-control functions) are three such basic categories of resource encountered in robotics. In more historical robotic architectures, resources were not often distinguished as such. Rather, these robotic sensors, effectors, and computational units were "hard-wired" functional components of a fixed, immutable larger vertically integrative algorithm, the control architecture. In the networked robotics context these resources become self-descriptive interfaces that make explicit the services they can export and incorporate scope for a range of local and remote connectivity options. The resources, thus encapsulated as modules, provide the basis for flexible, re-configurable robotic architectures mapped across multiple physical robot systems, namely a networked robot. The underlying paradigm is very powerful: Higher-level networked modules that autonomously inherit attributes of lower-level resources—*with emergent control and sensing properties*, as well as accompanying new module descriptors that themselves become the resources of yet further networked system aggregates. There are many potential instantiations of this idea that are purely autonomous and robotic, and some yet more classically telerobotic, including human agents [1, 23, and references therein]. In addition to the above reported work on robot work crew cooperation and reconfigurable robotic surface systems (R2S2), we also are carrying out more theoretical studies addressing such modular system synthesis, aggregation and resource modeling problems [24].

6. CONCLUSION

We have overviewed our recent research directed to advancing capabilities for robotic and ultimately human-robot interactive exploration of distant planets and moons of the solar system. Autonomy is fundamental to the practical and robust realization of such robots, due to their need for time-efficient, safe actions independent of real-time human supervision. We have illustrated this in the contexts of long range science roving, Mars sample return, all terrain mobility/access, and robotic outposts.

ACKNOWLEDGEMENTS

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